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STUDY OF HIGH ENERGY RADIATION ASSOCIATED WITH SOLAR FLARES AND AURORAL ZONE PHENOMENA

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For $26\frac{1}{2}$ years, NASA Headquarters provided supporting research and technology grants to the Space Sciences Laboratory (SSL) at the University of California, Berkeley for a study of high energy radiation associated with solar flares and auroral zone phenomena. As stated in proposals written over this period for the two successive grants that supported this study, the principal goals of the research and development efforts were:

1. *Development of new techniques for the identification and energy measurement of charged particles ranging in energy from several electron volts (eV) to millions of electron volts (MeV).* In addition to particle detection, a considerable effort was made to improve methods of photon energy measurement from a few kiloelectron volts (keV) to several MeV. Here the focus was on improved energy resolution and background reduction techniques. Some detector development was carried out at the Lawrence Berkeley Laboratory (LBL), located close to the Space Sciences Laboratory. In this way, new techniques in particle and photon detection developed at LBL could be, and often were, quickly adapted in our laboratory for space flight.
2. *Development of stable, high reliability subsystems required for space flight in order to condition and process signals received from the detectors.* Examples of such devices are low-noise, charge-sensitive preamplifiers; stable high voltage supplies for detector bias; and stepping high voltage supplies. For some years, a major development effort focused on means of passively cooling solid state detectors during space flight in order to lower the threshold at which the energy of charged particles and photons could be accurately measured.
3. *Development of laboratory facilities with which investigations of particle and photon detection methods could be carried out.* Some equipment items such as particle accelerators were acquired; others were designed and built in our laboratory. Standard laboratory equipment such as amplifiers, pulse height analyzers, power supplies, etc., were sometimes acquired from commercial vendors, but frequently they were designed and built in-house. Vacuum chambers of various sizes were also built, some with temperature-controlled interiors.
4. *Analysis and interpretation of data from sounding rockets and satellites when the support of flight hardware and data analysis contracts had expired.* The need to do this most often arose when new discoveries were made and additional insight into them could be gained by turning to the earlier databases. Earlier results could provide more examples, and could often be understood at a deeper level in light of subsequent findings.

In the pursuit of these four principal goals, the two Headquarters grants insured continuity of the efforts. In addition to these efforts, the grants made possible the participation of the Principal Investigator and other scientists in a variety of NASA-related activities. Examples are attendance at NASA/University Relations Conferences, and visits to NASA laboratories and commercial enterprises which manufactured detectors. Attendance at technical and scientific conferences which were relevant to our development work was also made possible by funds from these grants.

A few examples illustrating the value of long-term support for laboratory development of particle and photon detection techniques follow.

Development of Magnetospheric and Interplanetary Particle Detection Techniques. In the late 1950's a sounding rocket flight into a bright aurora had succeeded in making the first direct measurements of auroral electrons in the keV energy range. This effort was led by Dr. C. E. McIlwain, then at the University of Iowa. The Iowa success attracted the interest of other research groups, but it was clear to all these groups that improved particle detection methods would be needed for definitive studies of auroral particle phenomena. Dr. L. A. Frank, also at Iowa, introduced channeltron detectors on several OGO spacecraft and successfully made the first measurements of energetic particles in the terrestrial ring current. Energy discrimination was achieved by means of electric field deflection of the particles in a quadrispherical capacitor device. These early versions of channeltrons had significant limitations, which were soon alleviated for the most part by an innovation made by D. S. Evans, then a graduate student in the Physics Department here at Berkeley.

In the mid-1960's, with support from the initial Headquarters grant, we began to build on these particle detection efforts, implementing a systematic program of developing auroral particle detection techniques. Interest centered on hemispherical analyzers with channeltron counting devices. Typically, over the years, this effort involved a graduate student, a technician and a physicist, all of them working only part of their time on this project. Among the parameters we wanted to evaluate were the energy resolution and the geometric factor, especially as a function of the direction of particle arrival. In the laboratory, electron guns providing a collimated beam were used, as was ray tracing. Such devices were used through the 1970's, but it then became clear that the hemispherical and quadrispherical analyzers available at the time had serious limitations. Rocket and satellite results were showing that the plasma distribution function could change too rapidly in time and space to be followed by these detector systems. In the very early 1980's, Dr. C. W. Carlson, of our group, and Dr. G. Paschmann, of the Max Planck Institute, Garching, Germany, made a major innovation in the design of electric field particle analyzers. Their device is often referred to as the "top hat analyzer." It is now the instrument of choice when high time and energy resolution are required for auroral, magnetospheric, and interplanetary charged particle measurements. It has flown on several major spacecraft missions with great success, and is scheduled on several other flights. It has also been used on many rocket flights as well.

During the lifetime of these grants, a variety of special purpose analyzers was developed, and many of them eventually flew on rocket and/or satellite experiments. Examples of these detectors are large geometric factor electron detectors for very high time resolution studies, and ion analyzers to study phenomena such as arrival-time differences of ions which entered the Earth's distant magnetosphere and eventually arrived at altitudes of a few hundred kilometers.

X-ray Detector Development. Beginning with a balloon flight launched on the evening of June 30, 1957, just hours before the opening of the International Geophysical Year, Dr. J. R. Winckler, of the University of Minnesota, showed that bremsstrahlung X-rays from $\gtrsim 30$ keV electrons associated with visible auroras could be readily detected at altitudes easily accessible to inexpensive long-duration balloons. This discovery was quickly exploited in the U.S. and Europe. A major improvement was made in 1958 by using sodium iodide scintillation crystals instead of Geiger-Müller tubes. The NaI(Tl) detectors had efficiencies hundreds to thousands of times greater than the Geiger-Müller tubes. Much work was done under the first of the two subject grants to improve the low energy threshold for X-ray photon detection. This involved acquiring thin, cleaved crystals covered by high purity beryllium windows. We also undertook a program of evaluation and selection of photomultiplier tubes, which could take advantage of the much reduced low energy threshold of the scintillator assemblies. This development had immediate application to a quite different scientific problem – energetic X-rays from solar flares. These X-rays were believed to be due to bremsstrahlung of fast electrons accelerated in the flare process as some of these electrons plunged into the denser parts of the solar atmosphere. Such detectors were flown with great success on the OGO-5 and ISEE-3 spacecraft, permitting a comprehensive study of solar flare X-rays over most of two successive solar activity cycles.

A parallel development sought to greatly increase the sensitive area of the NaI(Tl) detectors. The immediate motivation for this was the desire to search for X-rays from the planet Jupiter. By the early 1970's, it was known to have a magnetosphere with very high intensities of trapped energetic charged particles. Some of these particles must be electrons which presumably precipitate into the dense Jovian atmosphere, just as they do in the case of Earth. Therefore, Jupiter must be a source of bremsstrahlung X-rays, probably a sporadic one. With additional NASA support, we developed a large area, low background detector and an oriented platform to track the planet. Flights were successfully made from Australia, but no X-rays were detected above the backgrounds. This was not entirely a disappointment since various models for causes of precipitation had been advanced, and it was possible to rule out several of these. In addition, the Australia flights measured solar flare X-ray emissions which varied extremely rapidly in time. Based on these measurements, we were able to eliminate certain theoretical flare acceleration models. The results were published in the journal *Solar Physics*.

The detector design was found to have many desirable basic features, and we decided to develop it further. The first change was to use lithium-doped germanium detectors. Then a major effort led by R. P. Lin, of our group, was made to further reduce the background counting rate. When the improved system was flown, true and undistorted solar flare X-ray energy spectra were obtained for the first time in the 15 keV to 300 keV energy range. Further development has led to the use of these detector systems on long duration balloon flights in the polar vortex winds above the Antarctic continent. At this writing, our Max 91 balloon program, which coincides with the solar maximum, is underway, with these advanced detectors playing a major role.

Development of Solid State Si(Li) Detectors for Measurement of Low Energy Electrons and Heavy Ions. In the mid to late 1960's, spacecraft measurements in interplanetary space and measurements near Earth's bow shock wave revealed populations of particles whose energies must extend below the thresholds of instruments being used at the time. For some populations the particle intensities were too low for the instruments of that era to obtain statistically accurate energy spectra. We, therefore, began a development effort using funds from both of the subject grants to develop instruments that would overcome the shortcomings revealed by IMP and other scientific spacecraft.

We chose to work with Si(Li) detectors in simple telescope arrangements, and even a single detector configuration for the very lowest energy particles (~ 10 keV). To obtain good energy resolution, the thermal nose in the detectors had to be reduced by cooling. We developed passive cooling methods using thermally isolated radiators and were able to cool detectors down to -60°C or even -80°C. In order to be useful on small scientific spacecraft, the "cold plates" could not consume electrical power, and they had to be low in mass. This scheme is vulnerable to electrical noise, and considerable effort was needed to eliminate pickup. The preamplifiers needed to be cooled as well, and a number of other technical issues had to be dealt with. One of these was the discovery in our laboratory of a very thin dead layer in the silicon detector itself. It was found to be about 8 $\mu g/cm^2$ in depth. Since silicon is a low atomic number material, this depth amounted to a considerable stopping power and was especially serious for heavy ions. An ion accelerator capable of producing ion beams up to ~ 150 keV total energy was donated to the laboratory by the Aerospace Corporation. After repairs and improvements to this accelerator, we made a comprehensive series of measurements on several Si(Li) detectors. The SSL accelerator was fitted with ion sources for the elements H, He, C, N, O, Ne and Ar. Other measurements were made at Lawrence Berkeley Lab (LBL), with an accelerator there that produced beams of S, Si, Mg, Fe, Ca, Ti, Ni, Xe and Kr.

In sum, the continuity of support for laboratory development of particle and photon detection techniques such as the examples described here was important from several points of view.

1. Intensive and steady work allowed us to make improvements and innovations on particle and detection sys-

tems that were at, or close to, the state of the art when appropriate NASA or ESA spaceflight opportunities arose.

2. Techniques often could be transferred from one development effort to another in an efficient manner.
3. The continuity allowed the detector technician, although working only part-time, to keep up on developments in the field generally, and especially in nuclear science laboratories such as LBL.
4. The sustained presence of an active particle and photon detector development laboratory was important to our commitment to graduate student training. We required our students to be involved in a broad range of scientific activities: hardware work, field support, data reduction and analysis, and interpretation of data. Their exposure to the laboratory development of flight hardware supported by the NASA grants was very valuable to our role in graduate education.

A list of publications resulting from the last two years of grant NGL 05-003-017 is appended. Previous publications resulting from this grant were reported to NASA annually, as a portion of our renewal proposals.

APPENDIX

Recent Publications Resulting from Research Supported by Grant NGL 05-003-017

Average ion moments in the plasma sheet boundary layer, W. Baumjohann, G. Paschmann, N. Sckopke, C. Cattell and C. Carlson, *J. Geophys. Res.* **93**, 11,507, 1988.

Filament eruption and the impulsive phase of solar flares, S. W. Kahler, R. L. Moore, S. R. Kane and H. Zirin, *Astrophys. J.* **328**, 824, 1988.

Lunar surface magnetic field concentrations antipodal to young large impact basins, R. P. Lin, K. A. Anderson and L. L. Hood, *Icarus* **74**, 529, 1988.

X-ray and radio properties of solar ^{3}He-rich events, D. V. Reames, B. R. Dennis, R. L. Stone and R. P. Lin, *Astrophys. J.* **327**, 998, 1988.

Average plasma properties in the central plasma sheet, W. Baumjohann, G. Paschmann and C. Cattell, *J. Geophys. Res.* **94**, 6597, 1989.

Solar flare nuclear gamma-rays and interplanetary proton events, E. W. Cliver, D. J. Forrest, H. V. Cane, D. V. Reames, R. E. McGuire, T. T. von Rosenvinge, S. R. Kane and R. J. MacDowall, *Astrophys. J.* **343**, 953, 1989.

On-board data analysis techniques for space plasma particle instruments, D. W. Curtis, C. W. Carlson, R. P. Lin, G. Paschmann, H. Rème and A. Cros, *Rev. Sci. Instr.* **60**, 372, 1989.

High-frequency electrostatic waves near Earth's bow shock, T. Onsager, R. Holzworth, H. Koons, O. Bauer, D. Gurnett, R. Anderson, H. Lühr and C. Carlson, *J. Geophys. Res.* **94**, 13,397, 1989.